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Syn-deformational features of Carlin-type Au deposits

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Abstract

Syn-deformational ore deposition played an important role in some Carlin-type Au deposits according to field and laboratory evidence, which indicates that flow of Au-bearing fluids was synchronous with regional-scale deformation events. Gold-related deformation events linked to ore genesis were distinct from high-level, brittle deformation that is typical of many epithermal deposits. Carlin-type Au deposits, with brittle–ductile features, most likely formed during tectonic events that were accompanied by significant fluid flow. Interactive deformation-fluid processes involved brittle–ductile folding, faulting, shearing, and gouge development that were focused along illite–clay and dissolution zones caused by hydrothermal alteration. Alteration along these deformation zones resulted in increased porosity and enhancement of fluid flow, which resulted in decarbonated, significant dissolution, collapse, and volume and mass reduction. Carlin-type Au deposits commonly are hosted in Paleozoic and Mesozoic sedimentary rocks (limestone, siltstone, argillite, shale, and quartzite) on the margins of cratons. The sedimentary basins containing the host rocks underwent tectonic events that influenced the development of stratabound, structurally controlled orebodies.
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1. Introduction

Geologic investigations of Carlin-type Au deposits have been numerous (Christensen, 1993; Vikre et al., 1997; Tosdal, 1998) and epigenetic hypotheses for their genesis call for possible connections to igneous activity at depth, for complex evolution of tectono-thermal events, for inherent host rock permeabilities, for evolved meteoric fluids, oil brines, or orogenic fluids, and many other factors (Arehart, 1996; Ilchick and Barton, 1997; Hofstra and Cline, 2000). The two largest concentrations of Carlin-type Au deposits are in Nevada, USA and China. Comparative studies of these deposits in Nevada and China by Mortensen and Poulsen (1993), Li and Peters (1998) and Hofstra and Christensen (2002) have demonstrated similar characteristics of these deposits in both regions.

North-central Nevada, USA, contains many Carlin-type Au deposits of several types and sizes, which also contain elevated concentrations of As, Ag, Sb, and Hg and lesser concentrations of Cu, Pb, and Zn (Peters et al., 2003). The Carlin trend has produced more than 1555 tonnes Au, and total production in the region is over 2100 tonnes Au (Teal and Jackson, 1997, 2002; Bettles, 2002a; Thompson, 2002; Thompson et al., 2002) (Fig. 1). Nevada deposits are hosted in Paleozoic sedimentary rocks, consisting of limestone, siltstone, argillite, shale, and quartzite, on the western margin of the North American craton (Bagby and Berger, 1985) (Fig. 1). Chinese Carlin-type Au deposits are present in a similar setting in Paleozoic to lower Mesozoic rocks in sedimentary basins along margins of the Yangtze Precambrian craton (Peters, 2002).

Paleozoic sedimentary basins in Nevada and counterpart Mesozoic basins in China underwent protracted tectonic events that influenced the stratabound, structurally controlled, and complex nature of the orebodies. Regional- and district-scale structures served both as conduits and as host-structures. These structures have tectonic ages compatible with the age of introduction of Au-bearing solutions (Peters, 2000). Some structurally controlled deposits contain micro- and mesoscopic-scale deformation fabrics and textures that can be linked directly to paragenetic development of Au orebodies (Peters, 2001). Geometry of orebodies and ore textures commonly parallel structural features, such as folds and faults, and this implies that some parts of the orebodies formed synchronously with deformation and have spatial and genetic relations to the structural features. Many Carlin-type Au deposits associated with zones of tectonic deformation also contain zones of collapse and volume loss due

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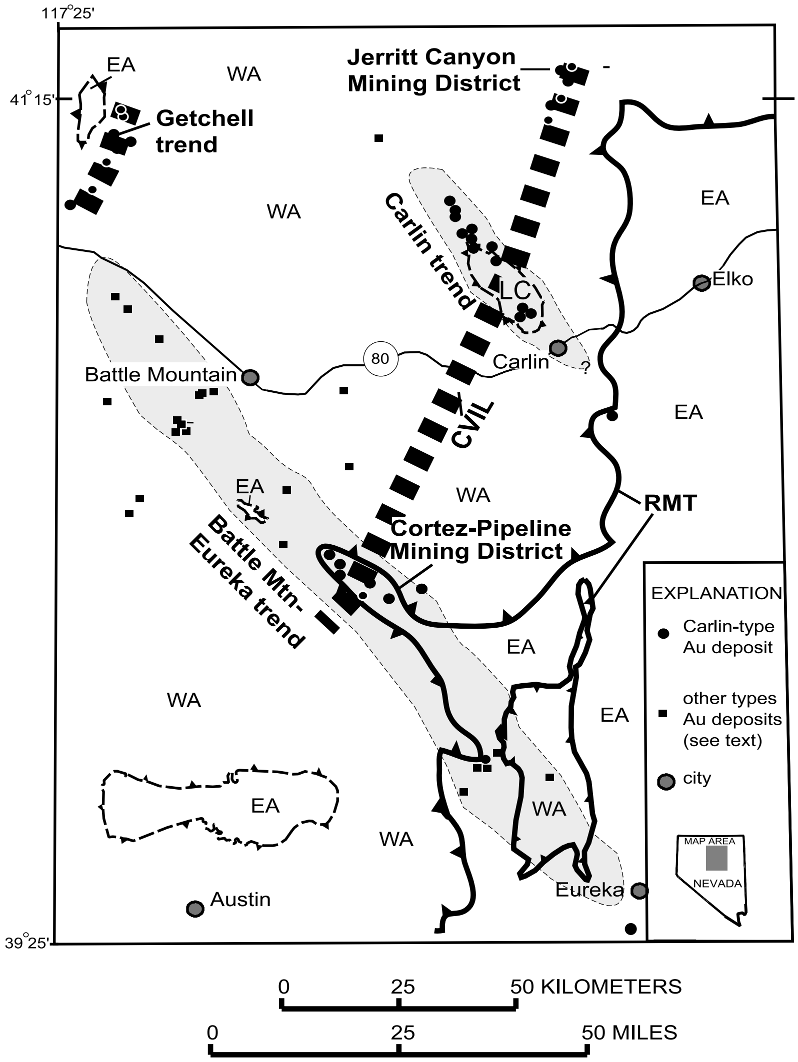

Fig. 1. Schematic geologic map showing distribution of Carlin-type and other Au deposits, and major mineral trends, in northern Nevada. Carlin trend (shaded) lies along the Lynn–Carlin window (LC) where several Carlin-type Au deposits are exposed. Other windows of platform limestone rocks (eastern assemblage = EA) through the Roberts Mountains thrust (RMT) and allochthonous siliciclastic rocks (western assemblage rocks = WA). The northwest-trending Eureka–Battle Mountain trend (shaded) crosses the Cortez–Pipeline Mining District. Jerritt Canyon and Cortez–Pipeline Mining Districts are at the north and south ends of the northeast-trending Crescent Valley–Independence lineament (CVIL) (thick dashes). The Getchell trend (thick dashes) parallels the CVIL. Modified from Prihar et al. (1996) and Stewart and Carlson (1976).

to hydrothermal dissolution. In these deposits, structural movement and deformation was not only a mechanical process, but also involved a chemical process, in that ore fluids directly affected geometry and geochemistry of host rocks and orebodies. Zones of deformation were zones of metal concentration, and therefore the deformation process was also a process of geochemical concentration.

Age of Carlin-type Au deposits in northern Nevada has been interpreted to be Late Eocene (Hofstra et al., 1999)—that is, synchronous with a time span after Late Mesozoic compressional and during Early Cenozoic extensional tectonism. Teal and Jackson (2002) interpret multiple ages of Au mineralization on the Carlin trend. Features described in this paper that suggest syn-deformational orebody formation are not compatible with shallow-level, extensional tectonic environments implied from a Late Eocene formation age of the Nevada deposits.

This paper addresses the interrelation between deformation and hydrothermal solutions on host rocks to Au orebodies by summarizing the classification, genesis, geologic setting, and metallogeny of Carlin-type Au deposits in Nevada. Interpretations result from observations made from 1:500-scale bench mapping in hypogene ores in the Goldstrike Mine and 1:6000-scale mapping along parts of the Carlin trend, Nevada. Mapping was augmented by geochemical and scanning electron microscope analysis conducted at the U.S. Geological Survey, Menlo Park, and at the Mackay School of Mines, Reno. In addition, XRD analysis was conducted at the Mackay School of Mines for illite-crystallinity estimations that followed the methods of

Kisch (1991) and used both the half peak width and area measurements of <2-μm clay material. Examples are given of regional- district-, and orebody-scale syn-deformational features in the deposits and a syn-deformational conceptual model is proposed for the formation of some Carlin-type Au deposits. Although the source of hydrothermal fluids and metals differs in a number of genetic theories, syn-deformational processes may have provided a common concentrating mechanism in many deposits.

2. Classification and genesis

Classification of Carlin-type Au deposits is important because many deposits in northern Nevada contain >100 tonnes Au with grades of 20–30 g/t Au (Teal and Jackson, 1997, 2002), whereas other sedimentary rock-hosted Au deposits in the region have different characteristics and show smaller sizes and grades, suggesting that more than one process may have been involved in the genesis of sedimentary rock-hosted Au deposits in the region (Peters et al., 1996). Characteristics of Carlin-type Au deposits are those indicated by Percival et al. (1988), Arehart (1996), Berger and Bagby (1991), and Hofstra and Cline (2000). Mineralogy of the deposits is characterized by submicron-sized Au, commonly in the crystal structure of disseminated pyrite associated with arsenopyrite, and Au-bearing As-rich pyrite rims, as well as some base-metal sulfide minerals, such as chalcopyrite, sphalerite, and galena. Many deposits also contain abundant stibnite, realgar, orpiment, and barite, as well as Hg and Ni sulfide minerals (Hausen and Kerr, 1966; Bakken et al., 1989; Mao, 1991; Arehart et al., 1993). The most abundant host rocks are thin-bedded, flaggy, mixed carbonate–siliciclastic rocks (Fig. 2).

Hydrothermal alteration resulted in variably silicified, decarbonated, and argillized host rocks that include calcareous or siliceous sedimentary rocks, skarn, mafic metavolcanic, and felsic intrusive rock (Fig. 2). Carbon is commonly present in large masses of black, sooty sedimentary rocks in and around the orebodies (Radtke and Scheiner, 1970; Ballantyne, 1988). Decarbonation removed carbonate minerals and much of the Fe, Mg, and Ca. Remaining Fe was fixed as FeS and FeAsS minerals. Decarbonation generally led to complete removal of calcite and dolomite, with the carbonate content of the calcareous host rock decreasing from 30 to 40 wt.% to less that 1 wt.% (see also Peters et al., 2002a).

Carlin-type Au deposits are described as 'carbonate-hosted Au deposits' in USGS model 26a of Berger (1986) and Cox and Singer (1986). They also are referred to as sediment-hosted disseminated and sedimentary rock-hosted Au deposits (Arehart, 1996; Peters, 2002). Wang and Du (1993) classified Chinese Carlin-type Au deposits into three types according to host rock, and further divided them into five subtypes differentiated by geochemistry and mineral associations. Similar classifications have been described by Wang (1994), who recognized two main deposit subtypes, on the basis of amounts of Sb and As minerals. Geochemical modeling by Hofstra et al. (1991) and Woitsekhowskaya and Peters (1998) suggests that these subtypes are part of a continuum due to an evolving, cooling ore fluid titrating with the host rocks. Although Carlin-type Au deposits are characterized by relatively uniform, low Au grades, some hypogene deposits contain high-grade oreshoots of different mineralogical types that are complexly zoned (Peters et al., 1998).

Characteristics of Carlin-type Au deposits suggest genetic processes that can be linked to local- and regional-scale feeder zones and to permeable areas where meteoric, magmatic, and metamorphic waters mixed along lithologic or tectonic contact zones (Fig. 2). The deposits commonly are present at the interface between underlying carbonate platformal limestones and overlying siliciclastic sedimentary rocks (Fig. 2). Deposition of ore minerals was most likely at moderate to shallow depths of 1–4 km (Kuehn and Rose, 1995; Lamb and Cline, 1997) in contrast to near surface depths of formation of most epithermal deposits. Zoning, high-saline fluid inclusions, sheeted veining and other features characteristic of magmatic systems are lacking in Carlin-type settings.

3. Geologic setting and metallogeny

Geologic setting and metallogeny of Carlin-type Au deposits relates to their genesis and control. Host rocks are hydrothermally altered, structurally deformed, and mineralized and mainly consist of very low-grade metamorphosed sedimentary rocks and some igneous rocks. In general, Carlin-type Au deposits are present near subhorizontal sedimentary or structural transitional zones between carbonate and siliceous clastic rocks (Fig. 2). Protracted tectonic histories in Nevada provided geologic settings that enhanced probabilities for subsequent formation of the deposits.

Geologic history of Carlin-type Au deposits in northern Nevada involves lower and middle Paleozoic, deep-water, siliciclastic sedimentary and volcanic rocks that were thrust eastward approximately 75–200 km during the Late Devonian to Early Mississippian Antler orogeny (Roberts et al., 1958). These rocks compose the approximately 5-km-thick Roberts Mountains allochthon (Madrid et al., 1992), which was thrust over coeval shallow-water, carbonate-rich rocks of the continental platform, and age-equivalent rocks of the para autochthonous slope and shelf (Fig. 1). These rocks were, in turn, over-thrust during the latest Permian and Early Triassic by the Golconda allochthon (Silberling, 1975), which consists of uppermost Devonian to lower Upper Permian carbonate-rich turbiditic sandstone and basinal strata. These three packages of Paleozoic rocks lie above the boundary between the western edge of the North

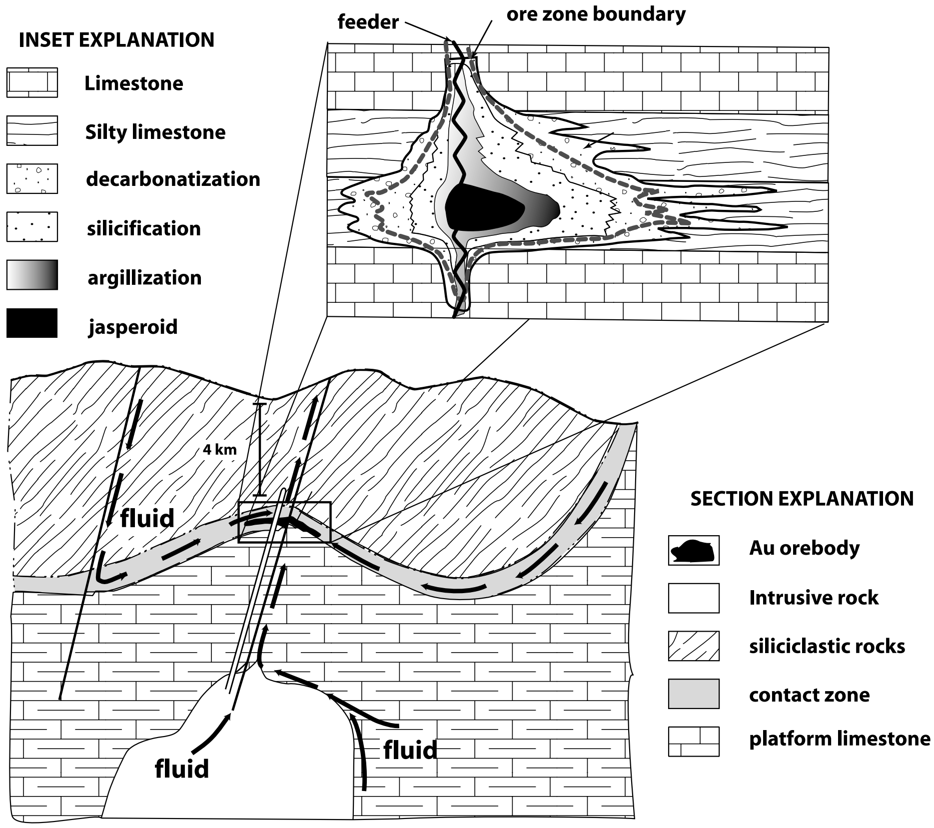

Fig. 2. Models for style and genesis of mineralization in Carlin-type Au deposits. Schematic cross-section shows pressure and fluid mixing processes, adapted from Kuehn and Rose (1995). Orebodies typically form below siliciclastic rocks near the interface with underlying Paleozoic platform limestone. Inset shows hypothetical detail of mineralized zone of barite, stibnite, orpiment, realgar, quartz and calcite with pyrite (+Au) surrounded by alteration halos of decarbonation, silicification, and argillization. Adapted from Kuehn and Rose (1995) and Arehart (1996).

American craton, which is composed of Archean and Meso Proterozoic crystalline basement overlain by allochthonous oceanic crust, and Proterozoic to Cambrian detrital rocks. Paleozoic and Mesozoic tectonic events produced crustal thickening marked by deformation above this older crustal boundary (Ketner and Alpha, 1992; Ketner et al., 1993) and all these rocks were further modified by regional-scale extensional detachment faulting in the late Eocene to early Oligocene, and by Mesozoic and Tertiary igneous activity that produced plutons and Tertiary volcanic rocks in the region (Seedorff, 1991; Thorman et al., 1991; Wallace, 1991).

Most Carlin-type Au deposits are hosted in platformal Silurian and Devonian impure limestone (Armstrong et al., 1997; Jory, 2002). Overlying allochthonous Ordovician, Silurian, and Devonian siliceous rocks also are mineralized, but most contain smaller, oxidized deposits with lower Au grades than deposits in the platform limestones of the lower plate. Most deposits are spatially associated with domal tectonic windows through the Roberts Mountains allochthon or with structural highs beneath the allochthon. Ages of the deposits are interpreted to be either Late Cretaceous or Early Eocene (Hofstra et al., 1999), which indicates that Au deposition was synchronous with or closely followed magmatic activity and regional high heat flow.

The Carlin and Getchell trends, and Jerritt Canyon and Cortez–Pipeline Mining districts contain a number of >100-tonne-size Au deposits with similar characteristics (Peters et al., 2003) (Fig. 1). The Carlin trend contains many northwest-trending meso- and megascopic folds and faults that define a structural domain separate from northeast-trending folds outside the trend (Peters, 1996) (Fig. 3). The Carlin trend parallels the Battle Mountain–Eureka trend, which is defined by a number of sedimentary rock-hosted Au and porphyry Cu–Au deposits. A northeast-trending lineament, the Crescent Valley–Independence lineament (CVIL), lies parallel to folds outside the trend and also crosses Carlin-type Au deposits in the Cortez–Pipeline district, the Carlin trend, and the Jerritt Canyon Mining District in the Independence Mountains (Figs. 1 and 3) (Peters, 1998).

4. Regional structural conduits

Lineaments, shear zones, faults, and porous lithologic units provided pathways for flow of Au-bearing fluids for Carlin-type Au deposits. Many Carlin-type Au deposits in northern Nevada cluster in mining districts that lie along northwest- or northeast-trending belts, such as the

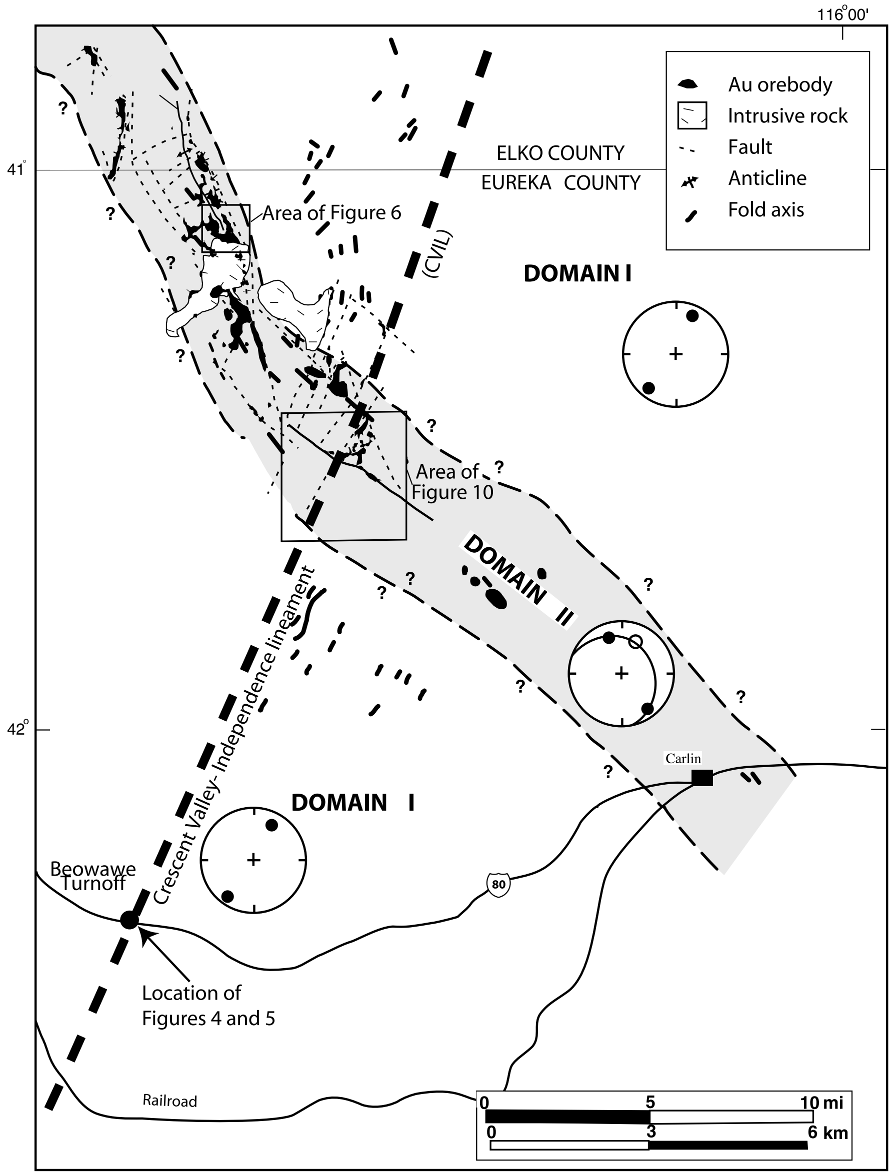

Fig. 3. Structural domain map of the Carlin trend area, outlining the Carlin trend on the basis of orientation of fold axes (dark circles in simplified equal area stereo nets). Trends of the shallow-plunging fold axes define two domains: Domain I contains a series of northwest- and southwest-plunging fold axes; Domain II, a local northwest-trending belt of northwest-trending fold axes that is roughly coincident with the Carlin trend and with the lower-plate tectonic windows of platform limestone. Some of the allochthonous siliciclastic rocks also contain northwest-trending fold axes along this zone. Small, short lines on map are fold axes compiled and cited in Peters (1996). The Crescent Valley–Independence lineament (CVIL) (Peters, 1998) traverses across the central part of the Carlin trend and is parallel to the fold axes in Domain I. For orebody names, see Teal and Jackson (1997).

Carlin or Getchell trends, or are associated with regional-scale lineaments (Shawe, 1991), such as the Battle Mountain–Eureka trend (Roberts, 1960; Thorman and Christensen, 1991) (Figs. 1 and 3). Lineaments have been postulated to be main conduits for metal-bearing fluids (Kerrich, 1986) and rocks along the structures interact with these fluids (Phillips, 1986; Hickman et al., 1994). Tectonically active conduits, accompanied by fluid flow, produced altered and mineralized fault rock textures and fabrics along deformation zones. The fluids then caused dissolution accompanied by deformation in or near the deposits.

Belts and lineaments are compatible with a number of genetic theories of Carlin-type Au deposit formation that call for deep-seated, over-pressured fluids and associated conduits (Kuehn and Rose, 1995; Lamb and Cline, 1997) (Fig. 2). Evidence suggesting that Au deposition was synchronous with tectonic movement along lineaments includes: (1) clustering of deposits along structural trends, (2) textures in some ores that are parallel to deformation fabrics, (3) high ore fluid pressures, indicated by fluid inclusion investigations and some ore textures, and (4) coincidence of local, late, highly deformed zones with alteration and(or) ore. Examples of regional lineaments that are spatially associated with Carlin-type Au deposits are the Carlin trend, the Eureka–Battle Mountain and Crescent Valley–Independence lineament (CVIL) in Nevada (Fig. 1).

4.1. Crescent Valley–Independence lineament (CVIL)

The Crescent Valley–Independence lineament (CVIL) in northern Nevada is defined by intense and varied deformation, igneous intrusions, and hydrothermal activity of several ages along a 90-km-long, N20°E- to N30°E-striking zone (Peters, 1998) (Figs. 1 and 3). Rock types near and in the CVIL contain fabrics that are typical of tectonic mélange zones (Peters, 1996, 1997a), such as fragmented and mixed rocks with phacoidal shapes in a scaly, shaley matrix (Fig. 4). In addition, jasperoid, breccia, quartz and calcite veins, and decarbonated zones are present along the CVIL. Outcrops near or in the CVIL retain consistent shallow-plunging northeast-trending linear fabrics, parallel to fold axes in the region and parallel to the strike of the lineament (Figs. 3 and 5), which is compatible with formation under tectonic, uniform stress along its entire strike length of approximately 90 km (see also Peters, 2000).

The CVIL traverses or is adjacent to three large Carlin-type Au districts (Fig. 1), is altered, and has anomalous Au, As, and Sb concentrations in rocks and soils (S. Peters, unpublished data). The lineament also was active during the time period when the Carlin-type Au deposits formed (Peters, 1998; Theodore and Peters, 1999). The expression of the lineament through the Carlin trend is a series of northeast-striking faults and northeast-elongate orebodies (see also Peters, 1999; Harlan et al., 2002; Jackson et al., 2002; Mohling, 2002). Deformation interacted with fluid that traversed along the lineament, particularly in permeable Paleozoic platform limestone (Fig. 5).

5. Examples of syn-deformational fabrics

Two examples of well-developed syn-deformational textures associated with Carlin-type Au deposits are found in the Betze Au deposit and in the Castle Reef fault zone along the Carlin trend, Nevada. Lithology and protracted tectonic history provided important deformation and mineralization components in these areas. Syn-deformational fabrics include ore and alteration minerals that are conformably oriented with surrounding L and S structures,

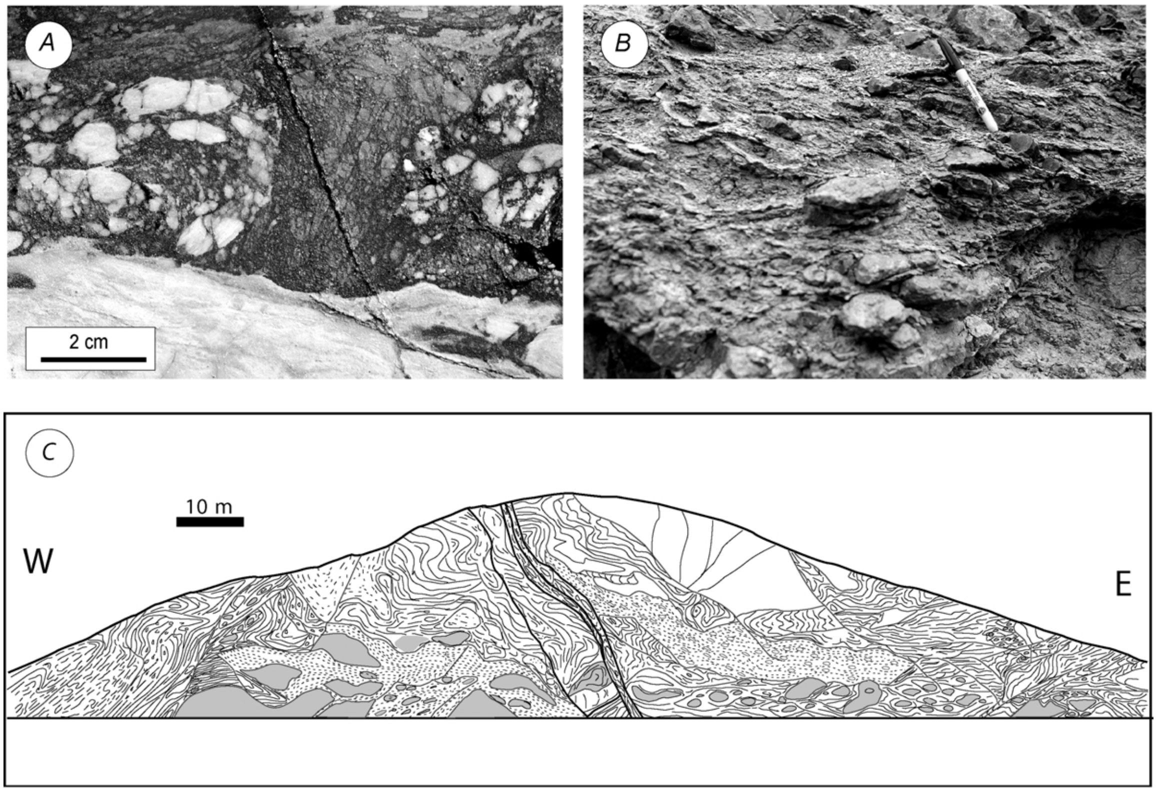

Fig. 4. Tectonized rock fabrics within the Crescent Valley–Independent lineament (CVIL), northern Nevada, near Beowawe turnoff (see Fig. 3 for location). (A) Photograph of tectonized chert showing mylonite at the bottom (white) and folded, brecciated, and rehealed bedding layers of chert on top. (B) Photograph of clast-in-matrix rock from shaley dolomitic sandstone (pen for scale). (C) Sketch of road cut through Crescent Valley–Independence lineament on Interstate 80. Solid lines represent form lines of undifferentiated bedding (S_0). Dashed and dash-dot lines indicate either bedding or foliation (S_1). Patterned or plain areas represent phacoids of competent rocks in sheared rock or clast-in-matrix rock (lensoid pattern). Rock types include laminated pelitic chert, massive chert, silty and calcareous sandstone, and massive dolomitic, fine-grained sandstone. See Peters (1996, 1997a) for detailed geologic legend and rock types.

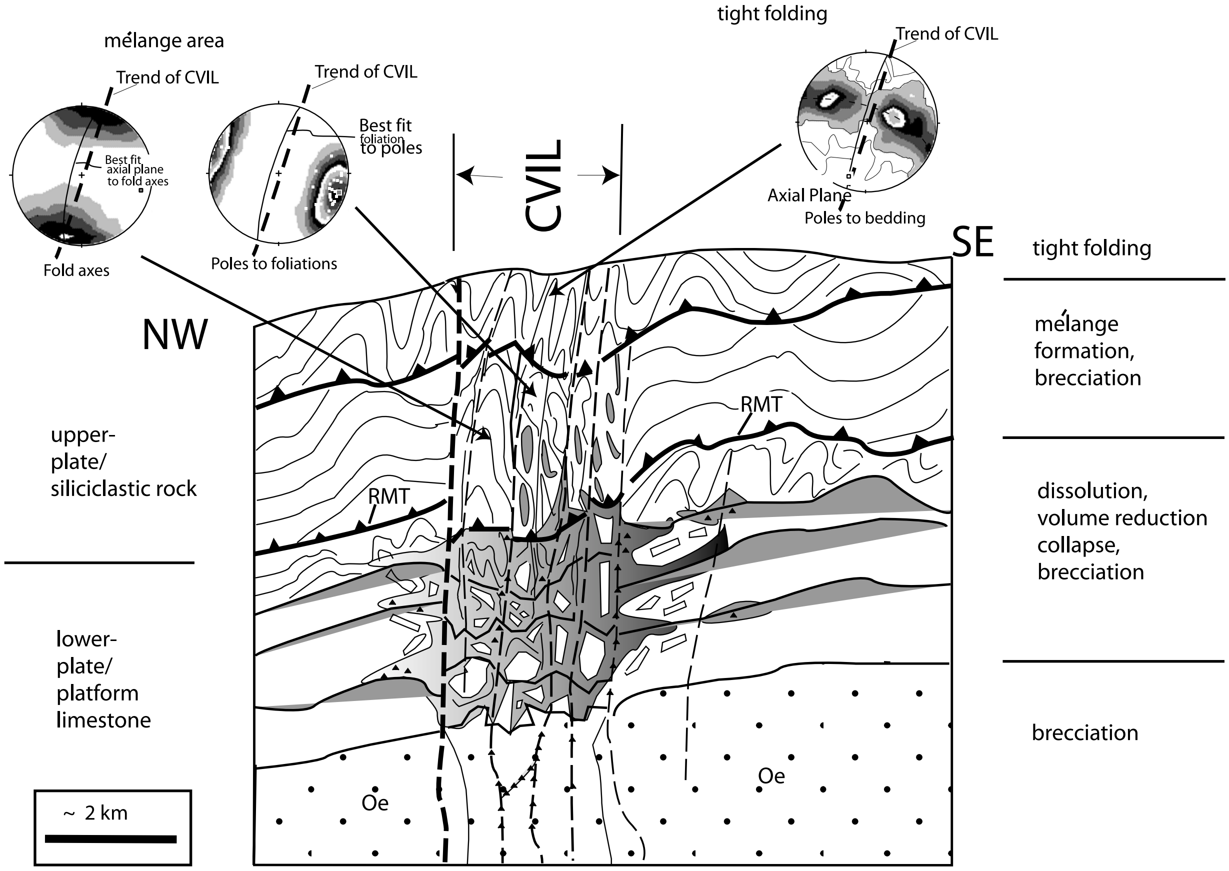

Fig. 5. Idealized cross-section through the Crescent Valley–Independence lineament (CVIL) at about 42° latitude north of Beowawe turnoff (see Fig. 3). The allochthonous siliciclastic rocks contain tight megascopic isoclinal folds and local gouge zones filled with jasperoidal breccia. The CVIL is parallel to the axial planes ($N = 476$, C.I. $= 2.0$ sigma on the contours of poles to bedding). The lower package of allochthonous siliciclastic rocks contains mélange rocks composed of clast-in-matrix rock and transposed folds with breccia zones (see Fig. 4C). Foliation in this zone is parallel to the CVIL ($N = 56$, 2.0 sigma contours), and fold axes ($N = 29$, 2.0 sigma contours) lie in the plane of the CVIL. The autochthonous formations of platform limestone provide the largest zones of fluid flow and were subjected to dissolution, volume reduction, collapse, and brecciation. Fluids traveled along the intersection of the limestone units and the CVIL, but also traveled outward along porous bedding horizons and cross structures. The Eureka quartzite (Oe), which contains narrow brecciated zones, restricted fluid flow. Modified from Peters (2000).

as well as wall rock phyllonite and local mylonite textures. Complex breccias of many origins also are common in many Carlin-type Au deposits (Peters et al., 1997), and are particularly common in many of the specific examples described below.

5.1. Betze Au deposit

The Betze Au deposit in northern Nevada along the Carlin trend (Figs 3 and 6) is the largest Carlin-type Au orebody, containing 1250 tonnes Au (Bettles, 2002a,b). It is composed of individual high-grade oreshoots that have different geologic, mineralogic, and textural characteristics (Peters, 1996, 1997b). The orebody lies at the northeast margin of the Jurassic Goldstrike stock within the west-northwest-trending Dillon deformation zone (DDZ) and Betze anticline (Fig. 6). Offset and sense of movement along the Dillon deformation zone (DDZ) are unclear. The orebody is hosted in thin-bedded, impure carbonate or limy siltstone, various types of breccia, and intrusive or calc–silicate rock (Leonardson and Rahn, 1996; Peters et al., 1998). Wall rocks near the orebody are intensely decarbonated and ore is sheared, folded (Fig. 9B), and brecciated with evidence of syn-deformational hydrothermal deposition (Figs. 7–9). Evidence for synchronicity of mineralization with deformation in the Betze Au deposit is demonstrated in: (1) deformed ore textures and alignment of alteration minerals (Fig. 9C and F); (2) characteristics of multiple breccia types; and (3) megascopic offset of mineralized ore pods by mineralized gouge and phyllonite (Fig. 9B and D).

Hydrothermal alteration includes decarbonation, argillization (illite–clay), and local silicification. Alteration zoning patterns in and surrounding the Betze Au orebody define a west-northwest-striking, large, porous, dilated volume of rock where high fluid flow predominated, possibly controlled, in part, by the north-northwest-striking post fault (Fig. 6). The DDZ contains the most intensely

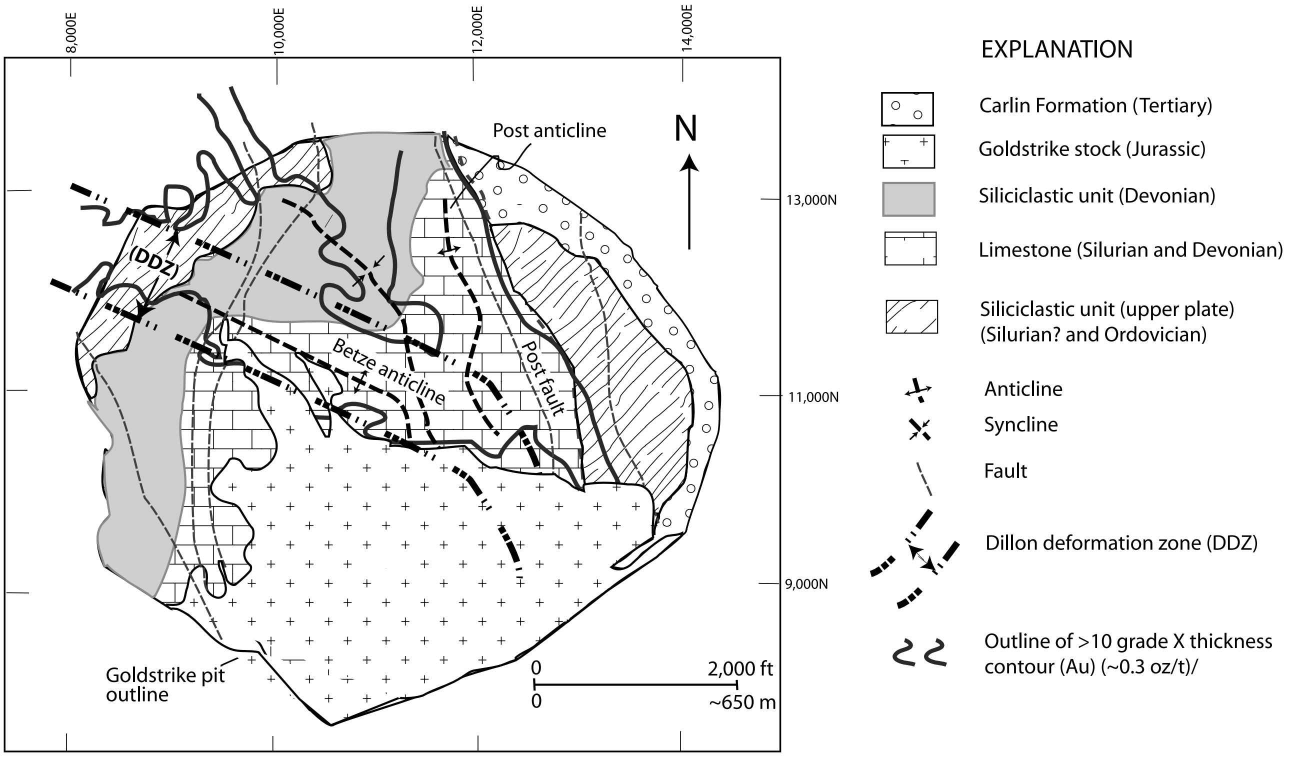

Fig. 6. Schematic geology and outline of Betze Au orebody associated orebodies in the Goldstrike Mine area, Nevada. See Fig. 3 for location along Carlin trend. The west-northwest-striking Dillon deformation zone (DDZ) lies along the Betze anticline. The DDZ has refolded the Post anticline. Coordinates are local mine coordinates; approximate longitude and latitude of center of map is 40°58′30″N, 116°22′45″E. Modified from Leonardson and Rahn (1996) and Peters et al. (1998).

altered rocks. Altered and tectonized host rocks have been converted to black–gray, carbonaceous phyllonite, decarbonated mudstone and gray limestone, clay-altered siliceous mudstone, calc–silicate rock, hornfels, diorite, and breccia (Figs. 8 and 9A). Upper, clay-altered parts of the orebody have ductile deformation textures, whereas lower, silicified parts show brittle deformation features. Pervasively sheared, 1–10-m-thick, phyllonitic strands are common throughout the DDZ, and undeformed phacoidal clasts, slabs, and blocks of limestone and marble are enclosed within sheared, pelitic layers that anastamose around them (Figs. 8 and 9A and B).

Breccia hosts much of the Betze Au orebody (Peters et al., 1997). Thick zones of tectonic breccia are most common in the DDZ accompanied by cataclasite, gouge, and phyllonite that have characteristics of fault zone rocks described by Sibson (1977), Ramsay (1980), and Tanaka (1992). Main breccia types include: (1) primary or secondary breccia along sedimentary beds; (2) cataclastic zones and fault gouge; and (3) breccia and phyllonite associated with strands of the DDZ (Fig. 8). These zones also contain discrete shear zones, gouge-filled brittle faults, and mesoscopic folds (Fig. 9B) Decarbonated collapse breccias contain 30–50 vol.%, centimeter-size, anhedral clasts of multicolored rock fragments, contained in a 50–70 vol.% fine-grained matrix of small, millimeter-scale rock fragments and illite–clay minerals. Breccia bodies are surrounded by seams of sheared, carbonaceous, illite–clay-rich phyllonite (Figs. 8 and 9D).

Crystallinity of illite in the Betze orebody is similar in phyllonite (0.36–0.54° 2θ), in clay fault gouge (0.38–0.41° 2θ), in decalcified rock (0.38–0.57° 2θ) and in illite–clay altered silty limestone (0.39–0.53° 2θ). The range of 0.2Δ2°θ in these rocks is close to the minimum value (0.1° 2θ) for the degree of confidence of illite crystallinity measurements discussed by Robinson et al. (1990). Similarity of illite-crystallinity values for altered, tectonized and decarbonated rocks suggests that clay minerals in these rocks reached similar temperatures and are compatible with synchronous deformation, hydrothermal alteration, and mineralization. Crystallinities of illite in altered diorite and calc–silicate rock (0.73–1.05° 2θ), suggest that either lower temperatures were reached in these rocks or may indicate addition clay minerals, such as smectite, that are interlayered with the illite.

Structural isolation of altered and mineralized cataclastic pods by phyllonite and gouge seams (Figs. 7–9) indicates repeated offsets along individual planar surfaces after and during mineralization. Deformation styles throughout the orebody also indicate that products of dissolution, transport, fluid flow, plucking, decarbonation, and high strain are spatially coincident with Au and its associated geochemical

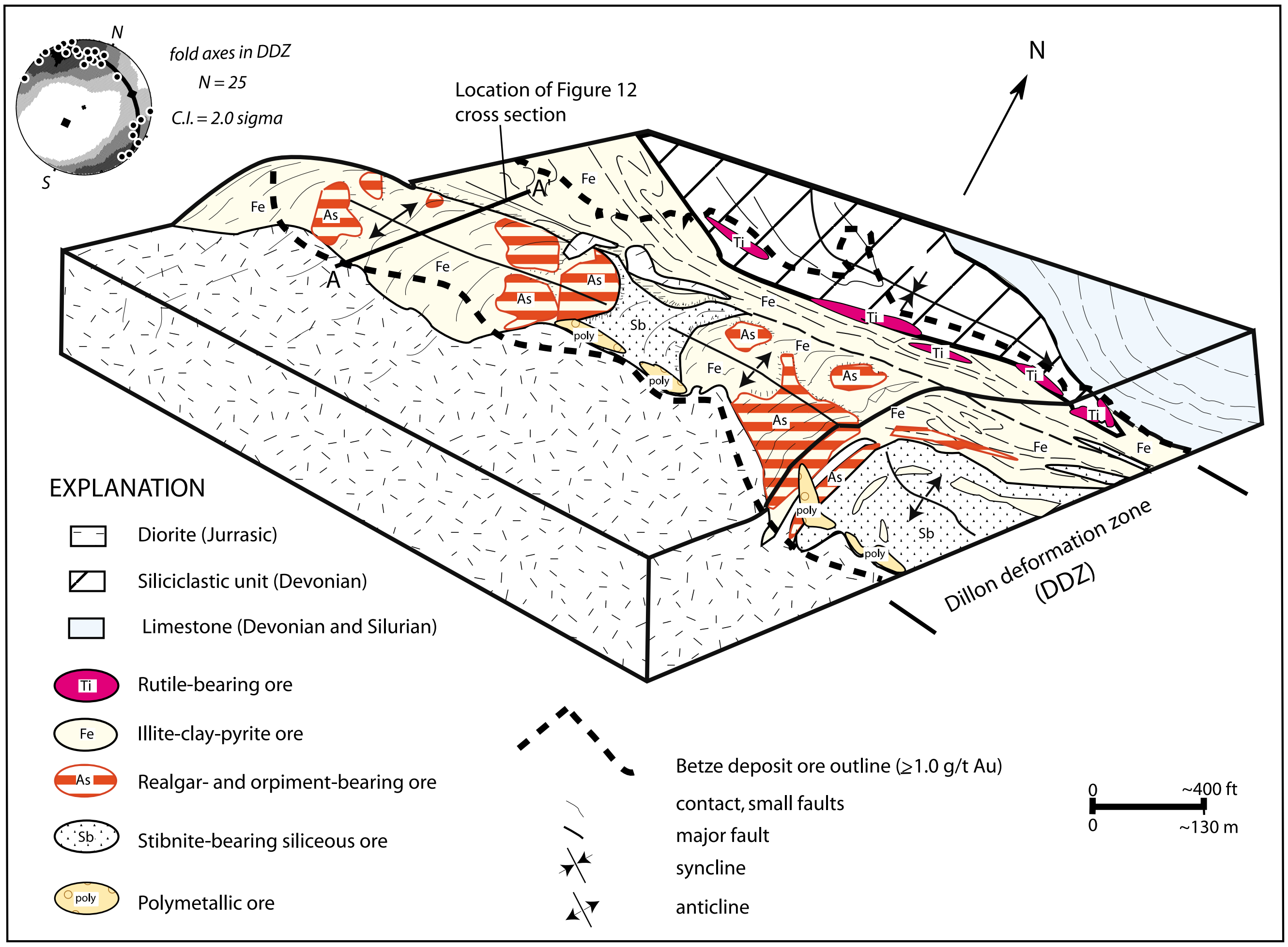

Fig. 7. Diagrammatic block diagram of the Betze Au orebody at about the 4600–5000 ft. elevation showing spatial distribution and zoning of oreshoots and their relation to the DDZ, Betze anticline, and syncline. For reference, see Fig. 6. Illite–clay-pyrite ores have internal pod-like geometries. Contact metamorphic and metasomatic rocks are not shown. Mineral deposition stages are: (1) illite–clay–pyrite and rutile-bearing ore, (2) realgar- and orpiment-bearing ore, (3) stibnite-bearing ore, and (4) polymetallic ore (see also Ferdock et al., 1997; Peters et al., 1998). Tectonic separation of these sequential ore types resulted from movement during ore deposition and from partitioning of fluid flow by gouge-filled seals. Interplay between rock types and pre- and syn-structural events can account for the distribution and zoning of the oreshoots. Contoured equal area stereonet shows axes of mesoscopic folds within the DDZ (best-fit circle to fold axes), which parallel the strike and plunge of the orebody. Note approximate location of section A–A′ for Fig. 8.

elements, and further suggests that hydrothermal and deformational events may have been linked in time and in space, such that mineralization and deformation were, at least in part, synchronous.

5.2. Castle Reef fault zone

The Castle Reef fault zone is a west-northwest-striking approximately 500-m-wide and 2-km-long deformation zone composed of folds, faults, and altered rocks that lies south of the Carlin Mine along the Carlin trend, Nevada (Figs. 10 and 11) and contains breccia zones and folds with west-northwest-, shallow-plunging fold axes that are parallel to the strike of the fault zone (Fig. 10). This zone has a similar orientation and textural characteristics to the DDZ in the Betze Au deposit. The Castle Reef deformation zone contains numerous hard, brown, tightly folded jasperoidal bodies along its margins that include dense, silicified breccia (Fig. 11A and B) and open-space brecciation. Local white, milky, quartz veins and zones of stibnite- and barite-bearing breccia are contained in some jasperoid bodies (Fig. 11C and D). In the center parts of the deformation zone, folds contain near horizontal fold axes with strikes that parallel the zone, but these zones are argillized and not silicified. Axial planes of mesoscopic and megascopic folds outside the Castle Reef fault zone are refolded from northeast- to north- to northwest-trending as they cross the Castle Reef fault zone from north to south (Fig. 10). The Castle Reef fault zone has been interpreted as a shear fold by Peters (1997c). The coincidence of jasperoidal and altered rocks and west-northwest-trending fold axes within the deformation zone, indicate that fluid flow either accompanied shear folding and brecciation in the zone, or preferentially penetrated the zone after

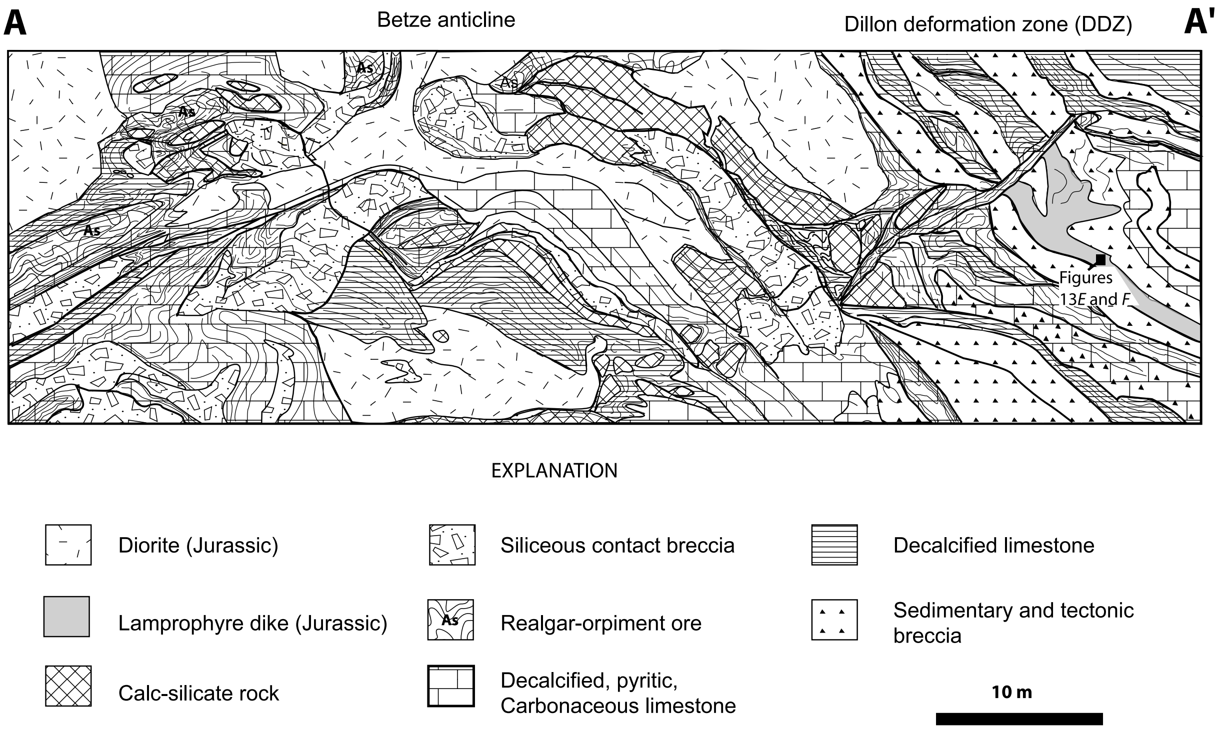

Fig. 8. Cross-section sketch A–A′ of mine benches looking west along axial plane of the Betze anticline and strike of the Dillon deformation zone (see Fig. 7 for location). Apophyses and sills of diorite are folded and brecciated along the anticline. Decarbonation and shearing are more common along the Dillon deformation zone. See text for description and interpretation.

deformation. Fluid that entered the zone produced broad zones of clay or silica alteration, and geochemically anomalous zones. These features along the fault zone are compatible with the zone being a focus for fluid flow.

6. Discussion

Structural fabrics associated with Carlin-type Au deposits and ore textures are reflected by the ore mineralogy and in the geometry of the host rock. These features allow construction of a conceptual model, which suggests that zones of deformation were also zones of metal concentration and that the deformation process was a process of geochemical concentration. Structural textures in orebodies and conduits represent pre-, syn-, and post-ore events, multiple fluid episodes, and various different fault offsets, as well as chemical replacements with specific geochemical signatures. Because orebodies contain mineral assemblages that differ from those outside the orebody, relations among mineralogical constituents may be used to interpret processes of orebody formation and paragenesis.

A conceptual model based on observed textures and structural features would involve ore fluids that were introduced into zones of structural complexity along pressure and temperature gradients. Differing porosity in these zones would have produced textural variation within, between, and along orebodies and along conduits due to fluid–rock interaction during deformation. The nature of ore deposition that may have formed during deformation would be indicated by the petrology of the conduits and the alteration assemblages that developed before and during deformation was in progress.

Typically, a central wall rock alteration zone is present in Carlin-type Au orebodies, and fringe zone alteration is present outside, along plunge or strike of the orebodies within the same conduit. Restriction of alteration assemblages to local meter-scale selvages implies that fluid flow in these areas was restricted. Broad alteration envelopes around orebodies indicate that the orebodies were sites of maximum fluid flow, which led to lateral dispersion of the ore fluid into the wall rock. In addition, more ‘reactive’ wall rocks resulted in wider alteration haloes than less reactive rocks along the same conduit. Alteration zones as wide as 1500 m, and intense and widespread decarbonation in some Carlin-type Au deposits, suggest that extremely high fluid flow took place in these systems.

A syn-deformational conceptual model implies that alteration not only affected rock strength but also played a chemical role in ground preparation, and silica introduction. Local concentrations of carbon within the orebodies may also have been important in the deformation history, because they represent areas of low shear strength and were therefore commonly areas of high strain. These rock strength changes would have produced localized ground softening or hardening (ground preparation). Ground softening (argillization or pervasive clay alteration) resulted in weak zones that localized faults and folds, such as along the

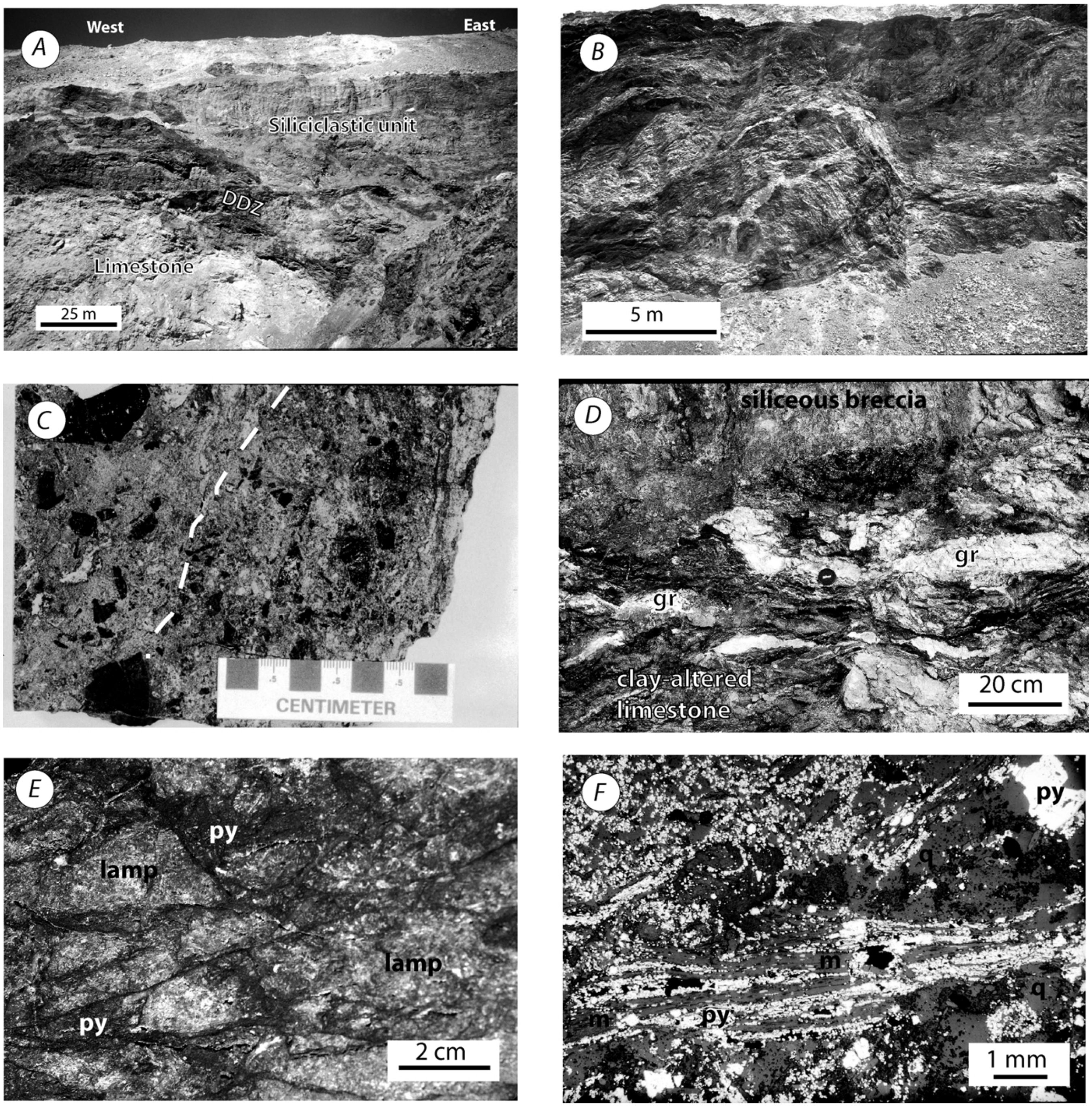

Fig. 9. Photographs of breccia and tectonized rocks in the Betze Au orebody, Goldstrike mine, Nevada. (A) Photograph of northwest side of Goldstrike pit showing cross-section of Dillon deformation zone (DDZ) that separates upper siliciclastic unit from decarbonated limestone. (B) Close up photograph, looking north, of DDZ showing folds and shear seams in brecciated decarbonated, carbonated, and pyritic limestone. (C) Cut slab of polygenetic breccia within DDZ of decarbonated limestone protolith. Dashed line shows approximate foliation or planar fabric, which is parallel to the attitude of the DDZ. (D) Deformed diorite (gr) apophyses parallel to phyllonitic seams that are interlayered with siliceous breccia in Betze anticline. (E) Cut slab of brecciated and decarbonated lamprophyre dike (see location on Fig. 8) with matrix seams of pyrite (and muscovite + quartz + apatite). (F) Microphotograph in reflected light of pyritic seam in (E) showing interlayering of oriented and foliated pyrite (py) and muscovite + quartz (m) in quartz + apatite (q) matrix.

DDZ and Castle Reef fault zone. Ground hardening (silicification), or increased host rock competency, allowed fracturing and brecciation, which also increased porosity and permeability.

Argillization took place during deformation in the Betze Au deposit, on the basis of similar illite crystallinity values in both altered host and fault rocks (Peters et al., 1998). Silicified breccia bodies and cataclastic zones, such as at the Betze Au deposit (Figs. 7–9) were isolated structurally by fault displacement and are surrounded by phyllonitic illite–clay seams and fault gouge (see also Moore et al., 1989). This indicates post-silicification shear zone movement.

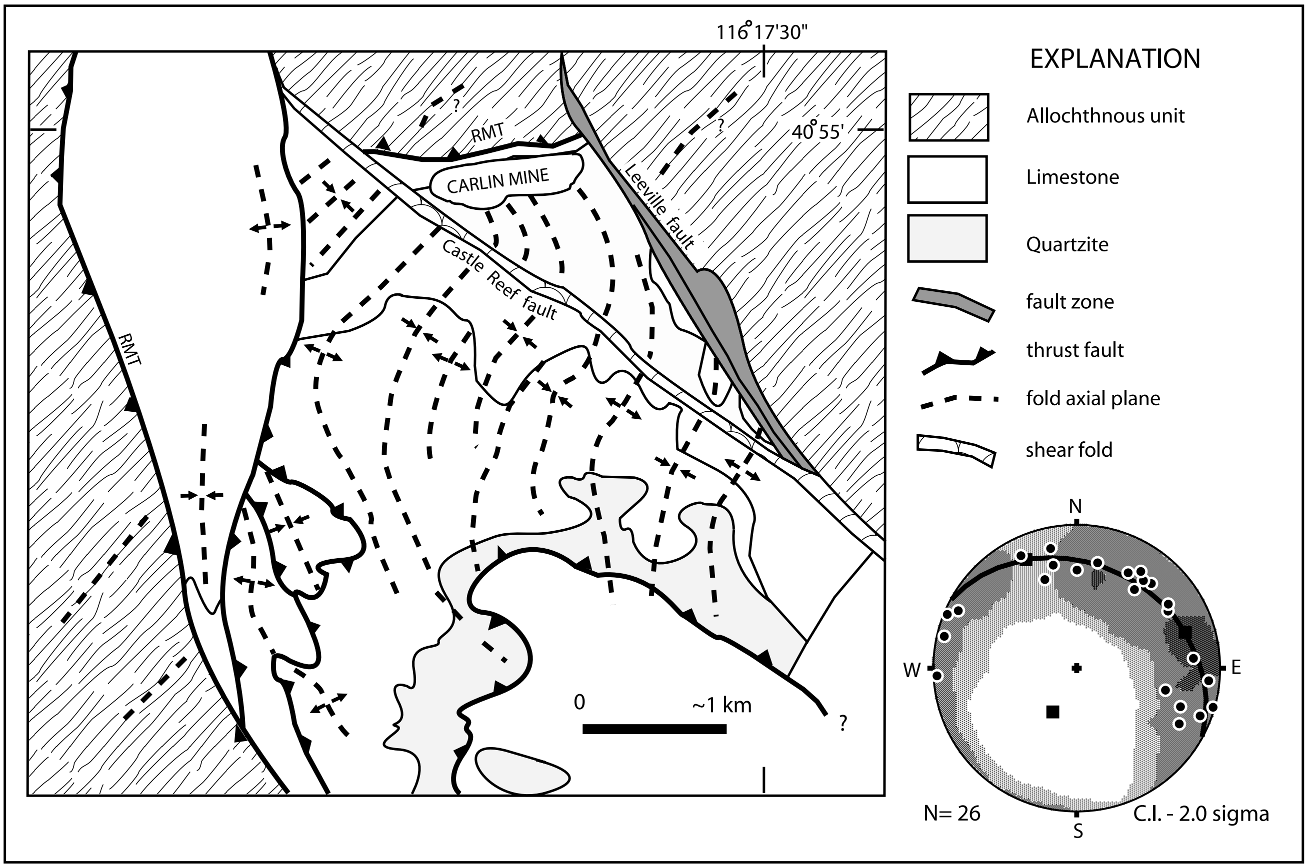

Fig. 10. Generalized structural geology of the north Lynn window, Carlin trend, Nevada. Megascopic fold axial planes (F_2) on the south side of the Castle Reef fault zone (F_3 shear fold) are refolded from north-striking to northeast-striking, to northwest-striking and on the north side of the Castle Reef, which is the orientation of most folds along the Carlin trend (see Domain I, Fig. 3). Equal area stereonet shows contoured fold axes within the Castle reef fault zone; the best-fit plane to these fold axes defines the strike of the fault zone. Note similarities in orientation to the Dillon deformation zone (DDZ) in the Betze orebody (Fig. 7). Adapted from Peters (1997c, 1999).

Zones of illite–clay alteration may have influenced chemical evolution of the fluid by hydrated clay minerals releasing or absorbing saline fluids under strain, and by planar illite–clay phyllonitic and gouge zones forming local pressure seals that channeled the fluids (see also Wang and Mao, 1979; Wang et al., 1979; Moore et al., 1989).

The syn-deformational conceptual model also takes into account the abundance and variety of ore-bearing breccias associated with the Betze Au deposit, which are consistent with a genetic relation between breccias and orebodies. Large parts of the host strata and connecting conduits of Carlin-type Au deposits are decarbonated along bedding-parallel layers of collapse breccia. Breccias were the loci for much of the fluid that precipitated Au and its associated minerals. Many collapse- and tectonic-related megabreccias in the Betze Au deposit contain or are bordered by mineralized illite–clay-rich phyllonite seams. These seams also enclose phacoidal blocks of limestone and marble at Betze, indicating that ore-fluid pathways followed these phyllonitic zones and that much of the dissolution and collapse was synchronous with strain (Figs. 7–9). Similar rocks are present in many Carlin-type Au deposits in China (Peters et al., 2002b,c), indicating that this process is a common feature of Carlin-type Au deposits.

Tectonic breccia, cataclasite, hydrothermal breccia, polygenetic breccias, and clast-in-matrix rock that are associated with Carlin-type Au deposits (Peters et al., 1997) typically have internal planar fabrics defined by clay-rich, brecciated fragments and phyllonite (Fig. 9C). These planar fabrics within breccia masses are related to deformation that occurred during or after dissolution and decarbonation, because they are composed of decarbonated and clay-altered material. In zones of clast-in-matrix rock, phyllonitic, anastamosing, or conjugate seams formed where strain and fluid were concentrated around the internally undeformed phacoidal blocks. These mélange-type fabrics and folding of clay-altered beds characterize many Carlin-type Au deposits, such as Betze, and also are common along regional-scale conduits that connect deposit clusters, such as the Castle Reef fault zone and CVIL (see also Peters, 1997b).

A syn-deformational conceptual model also suggests that strain within altered or mineralized deformation zones was heterogeneous and partitioned in each package of rocks,

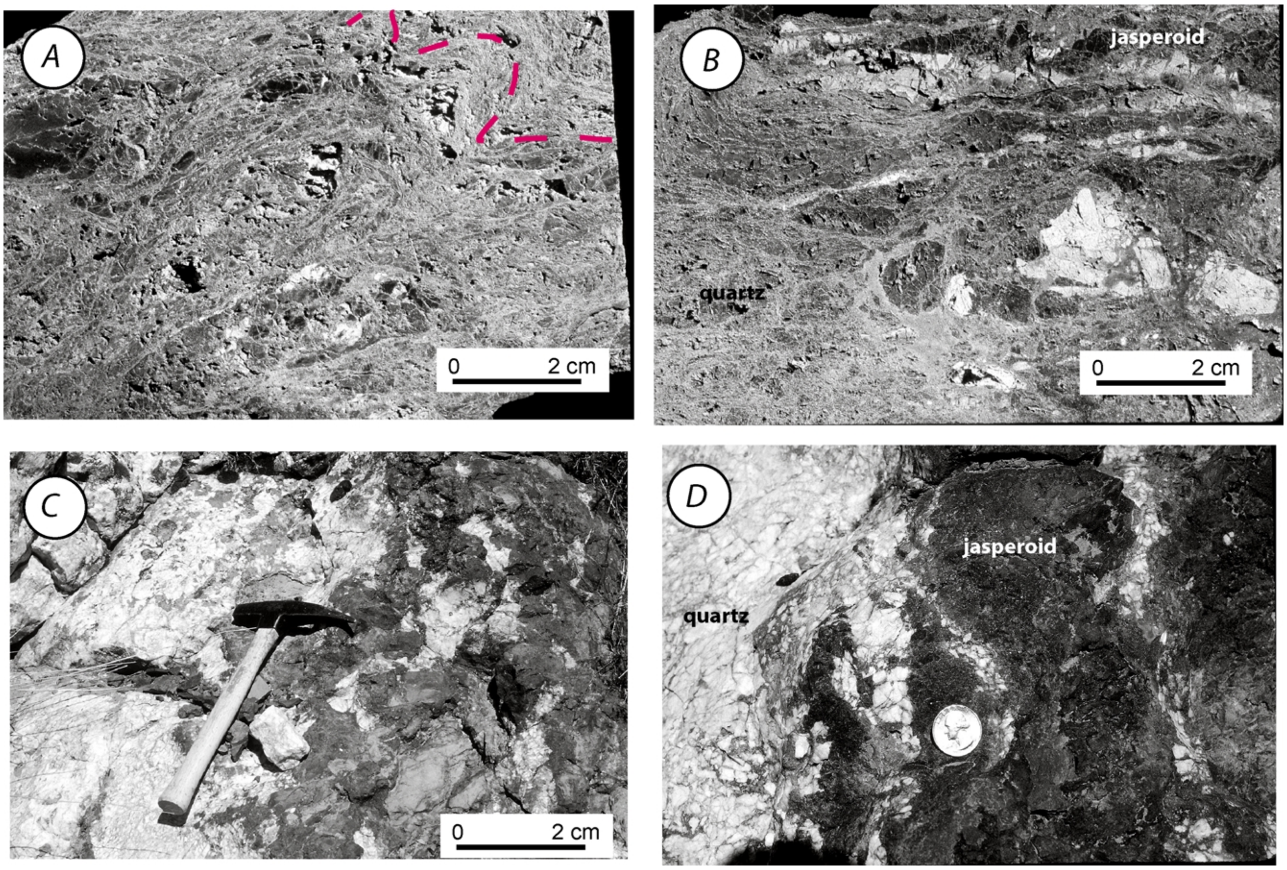

Fig. 11. Photographs of breccias and alteration in the Castle Reef fault zone, Carlin trend, Nevada. (A) Cut rock slab with folded and brecciated, decarbonated and silicified limestone. (B) Cut rock slab with brecciated and partially foliated decarbonated and silicified limestone. (C) Milky vein quartz and jasperoid along main part of fault zone. (D) Close up of quartz and jasperoid contact.

such that variation in deformation intensity and style among sheared, faulted, gouged or brecciated zones reflects rock type. Displacements were largely perpendicular to the walls of the deformation zones, because most of the volume change was from dissolution due to hydrothermal alteration (see also Ramsay and Huber, 1987). The Castle Reef fault zone has demonstrable simple shear displacement, on the basis of rotated mesoscopic fold axial planes adjacent to the zone (Fig. 10).

Along many deformation zones, such as the DDZ, however, displacement across the zones is more difficult to demonstrate, because of the intensity of dissolution and pure shear within the zones. Evidence of displacement and shear sense across deformation zones with large components of internal dissolution commonly is equivocal, and, therefore, a direct correlation between thickness of the zones and displacement along them cannot be made. In most Carlin-type Au deposits hydrothermal alteration and mineralization were confined to finite volumes accompanied by essentially nonrotational and coaxial deformation that produced folds, phyllonite, breccia due to dissolution, volume reduction, and collapse, within these intensely disturbed and altered rocks.

On a mining district scale, orientation and geometric relations among faults and tectonic breccia help constrain the timing of events. Close spatial relation among many Carlin-type Au deposits and their host structures are suggestive that structural and hydrothermal events associated with the deposits were derived from similar tectonic mechanisms. Oreshoots in the Betze Au deposit contain, or are separated by, complex mixtures of cataclasite, brecciated wall rock, gouge, phyllonite, illite–clay seams, and altered wall rock (Figs. 7 and 8), all of which are compatible with a complex dynamic ore forming system. Textural variations among the oreshoots along the deformation zone, such as at the Betze Au deposit, also suggest that local pressure and temperature fluctuations in the ore fluid may have occurred in conjunction with deformation and dilation.

Evidence that hydrothermal fluids transported metals over distances of more than 100 km has been described by Sverjensky (1984) in sedimentary basin settings similar to those where Carlin-type Au deposits are present. Applying these concepts to the CVIL zone, such fluids most likely migrated through locally porous, platform limestone (Figs. 4 and 5). If a 210–150 °C ore fluid with high CO_2, and moderate salinity—similar to the Carlin-type Au ore-forming fluid modeled by Woitsekhowskaya and Peters (1998)—was capable of producing Carlin-type Au deposits, it also was capable of transporting metals over regional-scale distances (see also Crerar et al., 1985). A syn-deformational conceptual model of Carlin-type Au systems involves fluid flow that was concentrated in the most highly permeable conduits, and that was accompanied by deformation, coeval dissolution, magmatism, and elevated crustal heat flow (Peters, 1998, 2000). Geologic features along the CVIL indicate repeated structural activity, which if associated with fluid migration, may have resulted in multiple Au deposits.

A conceptual model for syn-deformational formation of Carlin-type Au deposits would also involve deep faults that acted as high permeability conduits. These conduits guided fluid flow from depth and then laterally into the orebody environment, a mechanism proposed by Etheridge et al. (1983). Multiple conduits or separate parts of the same conduits may have connected at depth, resulting in the segregating of fluid flow in distal parts of the conduits.

Observations and interpretations presented above allow speculation that although mineralization characteristics are similar in separate parts of Carlin-type Au districts, orebodies, or oreshoot clusters, differences in tenor, strength, and structural control could be due to local structural and chemical conditions caused by local fluid evolution. Fluid evolution rate may have been dependent on the time and distance of separation from the parent fluid and titration of this fluid with the wall rock through which the conduit passed. Evolving stages of hydrothermal minerals associated with Au ore deposition may have overlapped due to cycling of circulating hydrothermal fluid, such that different mineral assemblages formed both sequentially and simultaneously (Ferdock et al., 1997). The >1-km-scale geometric flow paths allowed isolated avenues of fluid flow in a single ore district and spatially partitioned separate metallogenic episodes.

7. Conclusions

Strong field and laboratory evidence exists for the introduction of Au-bearing fluid during deformation and interaction of fluids within wall rocks. Syn-deformational Carlin-type Au orebodies commonly are present in zones of dilation and high fluid flow, indicating a complex history of development. Many of the orebodies are interpreted to have formed during tectonic events that were accompanied by significant fluid flow. The structural features discussed in this paper suggest that syn-deformational orebody formation are not compatible with shallow-level, extensional tectonic environments implied from a Late Eocene formation age of the Nevada deposits. Either brittle–ductile deformation must be considered as part of the Early Cenozoic tectonic framework or other ages or ore forming mechanisms should be entertained.

Geometric and structural characteristics on a number of scales indicate that parts of some Carlin-type Au orebodies or their regional conduits formed synchronously with deformation. Regional- and district-scale structural fabrics associated with the deposits are consistent with the ages of introduction of Au-bearing solutions. These regional-scale structures or lineaments may have served as both conduits and host-structures for Carlin-type Au deposits. Some structurally controlled deposits contain micro- and mesoscopic-scale deformation fabrics and textures that can be linked with paragenetic development of the orebody.

Carlin-type Au deposits in Nevada have a number of similar regional sedimentary and tectonic features: (1) all deposits are present near the margin of the North American craton, where craton-scale tectonic units are in contact; (2) deposits are hosted in Paleozoic sedimentary basins, which contain shallow-water platform limestone structurally overlain by siliciclastic sedimentary rocks; (3) a protracted history of both compressional and extensional deformation is evident; and (4) evidence of an alignment of geologic features reflects regional deep-crustal deformation zones that formed during major orogenies. Many or all of these features probably contributed to localization and formation of clusters of Carlin-type Au deposits.

The thesis presented here is that faults along regional-scale lineaments, district-scale faults, and deformation zones were active as fluid conduits before, during, and after formation of the Au deposits. In addition, the coincidence of the Au deposits with domal tectonic windows in northern Nevada suggests that structures within or adjacent to fluid conduits served as traps for the Au fluids. Fluid flow, accompanied by deformation along these conduits, produced jasperoidal rocks, silicified breccia, gouge, and phyllonite along or adjacent to these structures.

Deformation was an important mechanism in the formation of Carlin-type Au deposits. Ore genesis of Carlin-type Au deposits in northern Nevada may have involved a number of factors: (1) a single ore fluid may have traversed fault zones along lineaments, producing clusters of ore deposits in structural traps; (2) intersections of tectonic lineaments with these traps provided permeable foci that concentrated ore fluids; or (3) tectonism, crustal-scale hydrologic flow, and heat flow provided unique settings at different or multiple ages in each mining district. Faulting, folding, shearing, and gouge development along less competent illite–clay altered and decarbonated zones—accompanied and followed by collapse continued during hydrothermal alteration—increased porosity and enhanced fluid flow along deformation zones.

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